Design and Analyses of High Aspect Ratio Nozzles for Distributed Propulsion Acoustic Measurements

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Outline

- Introduction
- Nozzle Design Requirements
- Screening Simulations and Nozzle Grids
- Nozzle Designs
- Conclusions and Recommendations

Introduction

Turboelectric Distributed Propulsion Hybrid-Wing-Body Concept
NASA, Feb. 5, 2008

- NASA’s roadmap for future transport aircraft includes departure from tube-and-wing aircraft.
- Above: wingtip gas turbine engines power multiple electric-driven fans in mail slot distributed arrangement.
- Jet-Surface Interaction High Aspect Ratio nozzle tests conducted at NASA Glenn Research Center Nozzle Acoustic Test Rig (NATR) took acoustic measurements of similar configuration:
  - High aspect ratio, mail slot-like nozzle.
  - Septa inserts to mimic individual fan ducts.
  - Aft deck.
- Goal: design nozzle for NATR to simulate distributed propulsion system.

High Aspect Ratio Nozzle Requirements

Purpose: Design a series of round-to-rectangular high aspect ratio (HAR) convergent nozzles for NATR to simulate distributed propulsion nozzle system.

Requirements:

- HAR nozzle aspect ratios: 8:1, 12:1, 16:1.
- Inflow: circular, D=10.29 inches.
- Exit area: ~39.68 square inches.
- Max length: ~24 inches
  - NATR has free-jet around nozzle to simulating forward flight.
  - Maximum length ensures HAR nozzle plume is contained within NATR free-jet potential core.
- Constant span segment near exit for septa inserts.
- Minimize unfavorable flow characteristics that would potentially produce rig noise: flow separations, exit shocks.
- Near-uniform flow entering septa inserts.

Exit Dimensions of High Aspect Ratio Nozzles

Aspect Ratio	Height [in]	Width [in]	Area (A_{jet}) [in^2]	Equivalent Diameter (D_{eq}) [in]
8:1	2.227	17.820	39.685	7.108
12:1	1.818	21.822	39.672	7.107
16:1	1.575	25.197	39.685	7.108

Screening Simulations

- Wind-US v4 used for all simulations.
  - General purpose, compressible Reynolds-Averaged Navier-Stokes solver.
  - SST turbulence model used.
  - Steady flow simulations, i.e. constant CFL number.

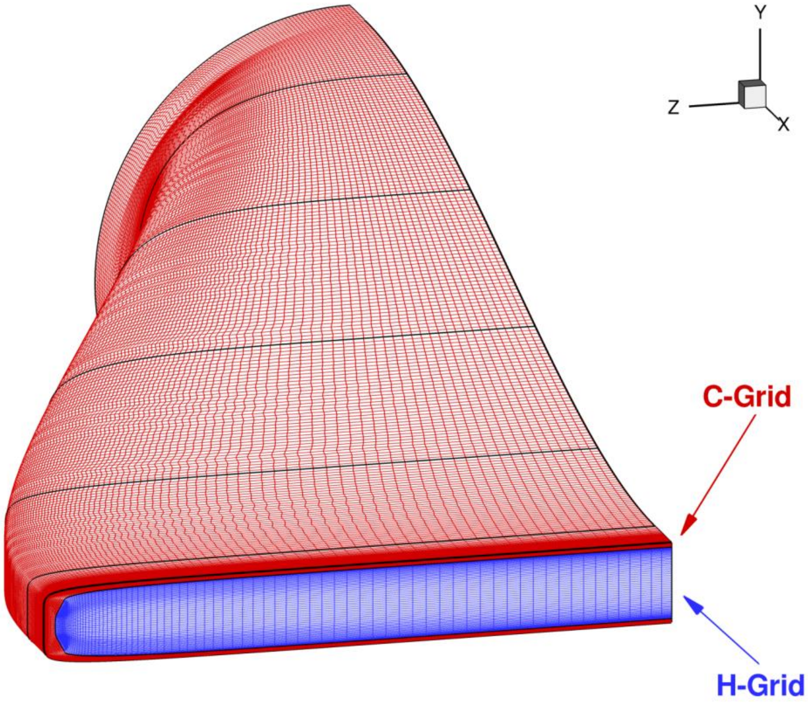
- Flow conditions for simulations used Tanna Matrix Set Point 7:
  - Quiescent Freestream: p_∞=14.3 psi; M_∞=0.01
  - NPR=1.861 → M_{jet}=0.98 (M_a=0.90)
  - "Unheated" Jet: T_0=529.64°R (T_{jet}/T_∞=0.835)
  - Did <u>not</u> simulate NATR free-jet (forward flight).

- Simulations performed on NASA Advanced Supercomputing System:
  - "Ivy Bridge" nodes, using 32-100 processor cores per simulation.
  - Typically, obtained converged solution in about a week.

High Aspect Ratio Nozzle Grids

- Two-step structured grid for HAR nozzle internal flow:
  - "C" grid along nozzle wall (**red**).
  - "H" grid through center of nozzle flow (**blue**).
  - Reduced highly skewed cells, singularities, unresolved geometry
  - Continued two-step grid through jet plume and external flow.
- Wall spacing: 0.0002 inches (nominal y^+=2).
- Farfield boundary: 30 inches ($4.2 \times D_{eq}$).
- Downstreeam boundary: 280 inches ($25.3 \times D_{eq}$).
- Grid size: 9.2 million to 33.5 million cells.

Two-Step Grid Topology



High Aspect Ratio Nozzle Designs

- Assumptions:
  - Aspect ratio 16:1 nozzle would be most challenging, since span grows the most (2.45x inflow diameter). Design AR=16:1 nozzle first, use similar techniques for AR 12:1, 8:1 HAR nozzles.
  - Round-to-rectangular nozzle could be designed as a backwards inlet using SUPIN (parameterized inlet design code).

- Nomenclature: A*x*.*y* nozzle design:
  - x=aspect ratio
  - y=nozzle design iteration
  - A16.2 → aspect ratio 16:1; design iteration 2

- Note: Only the more interesting nozzle designs will be presented. Some design iterations will be skipped.

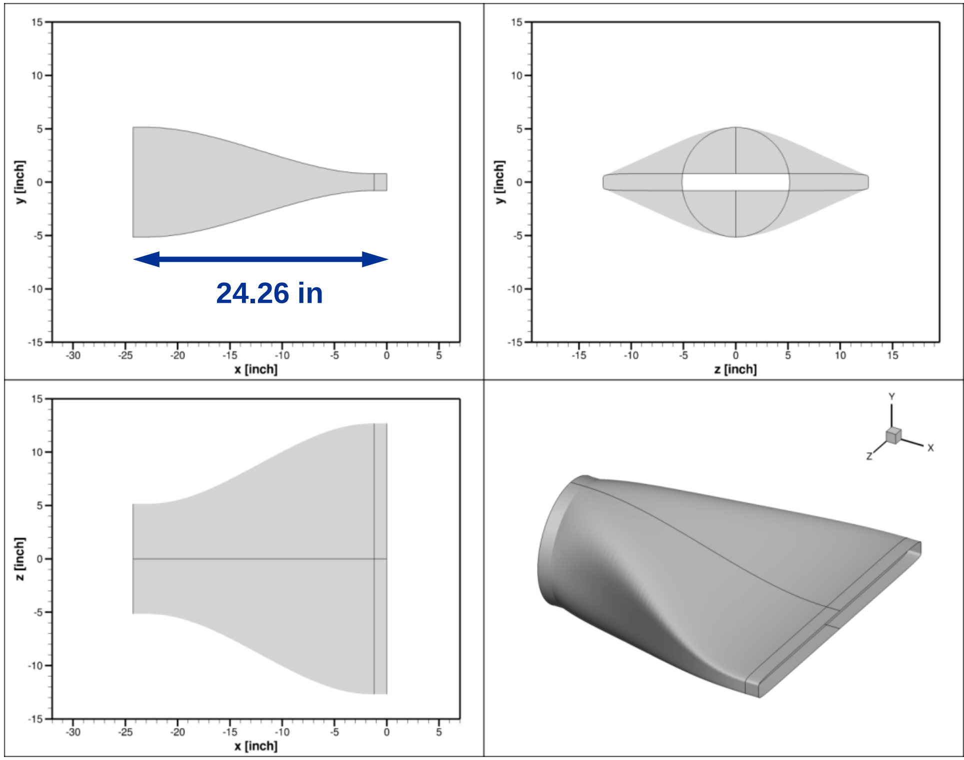
A16.2 Nozzle Design

- Used modified version of SUPIN.
  - SUPIN is a parametric inlet design tool by John Slater at NASA GRC (AIAA Paper 2012-0016).
  - Thought it could be a quick method to generate complex nozzle geometries.
  - John Slater delivered a version of SUPIN, adapted for nozzle geometry design.
  - Ran SUPIN to generate backwards nozzle designs.

- Set:
  - Inflow Area (RadEF)
  - Exit Area (FAcap)
  - Aspect Ratio (ARtopcap, ARbotcap)

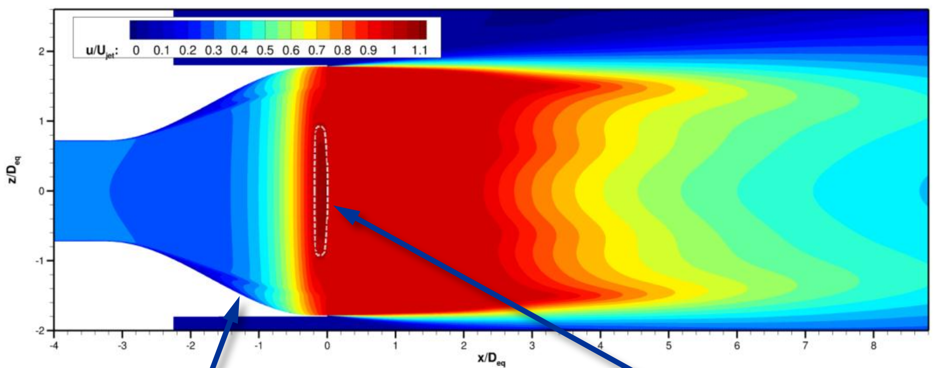
- Variable Parameters:
  - Total Length (FLsubd)
  - Length of Constant Area Exit (Lthrt)
  - Super-ellipse Parameter (ptopcap, pbotcap)
  - Y-position of exit (Yinlet)
  - NURBS CURVE Parameters (Xsdgc2, Fdsdgc2, Fdsdgc1, Fdsdgc3)

A16.2 Nozzle Design



A16.2 Nozzle Screening Simulation

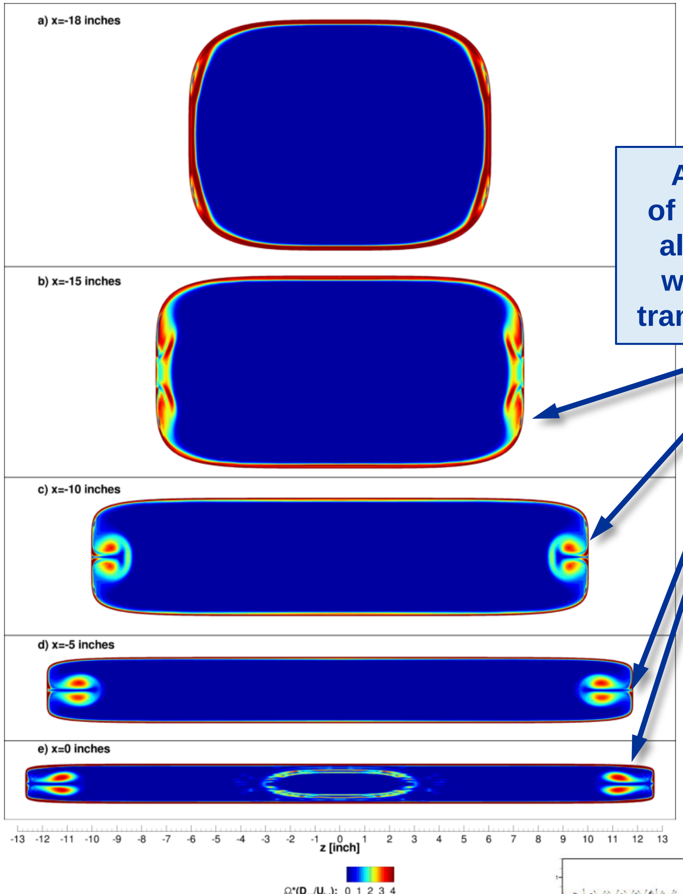
Velocity Contours Along x-z Symmetry Plane



Thick BL along outboard walls.

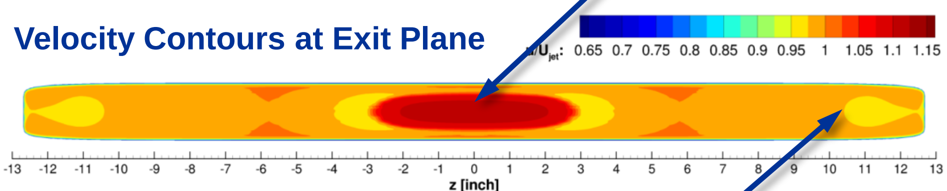
Region of supersonic flow, followed by shockwave. Possible aerodynamic throat?

Vorticity Contours Inside Nozzle



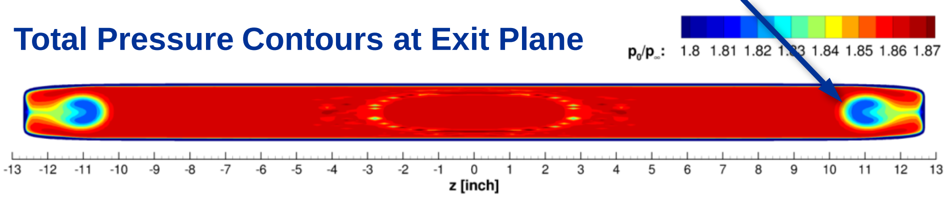
Apparent pair of vortices forms along outboard walls as nozzle transitions shape.

Velocity Contours at Exit Plane

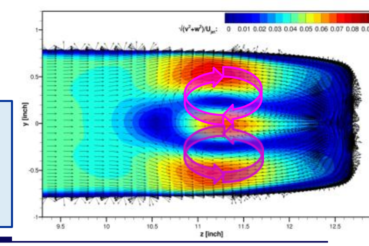


Velocity and total pressure deficit along outboard walls.

Total Pressure Contours at Exit Plane



Cross-Stream Velocity at Exit

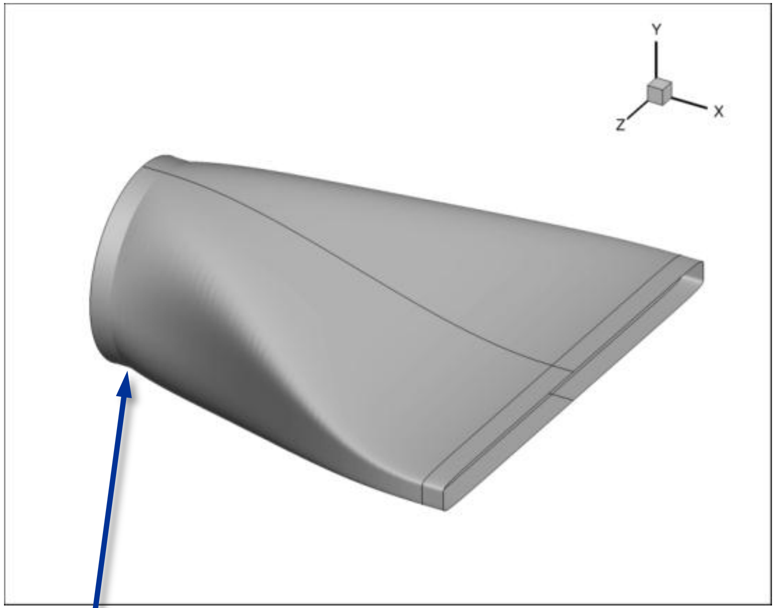


Cross-stream velocity vectors confirm counter-rotating vortex pair.

SUPIN-Designed HAR Nozzles

- Performed screening simulating of several HAR nozzle designs generated with SUPIN.
- Nozzles produced undesirable flow features:
  - Thick boundary layers and flow separation along outboard walls as span grew.
  - Non-uniform flow along outboard walls near exit plane: velocity and total pressure deficit; vortex pair.
  - Normal shock along centerline, likely due to aerodynamic throat from thick BL on sidewalls.
- SUPIN-generated nozzle designs were not always smooth near inflow.
- SUPIN was <u>not</u> adequate tool for generating nozzle designs.
  - Required greater ability to control and parameterize nozzle designs

A16.2 Nozzle Design

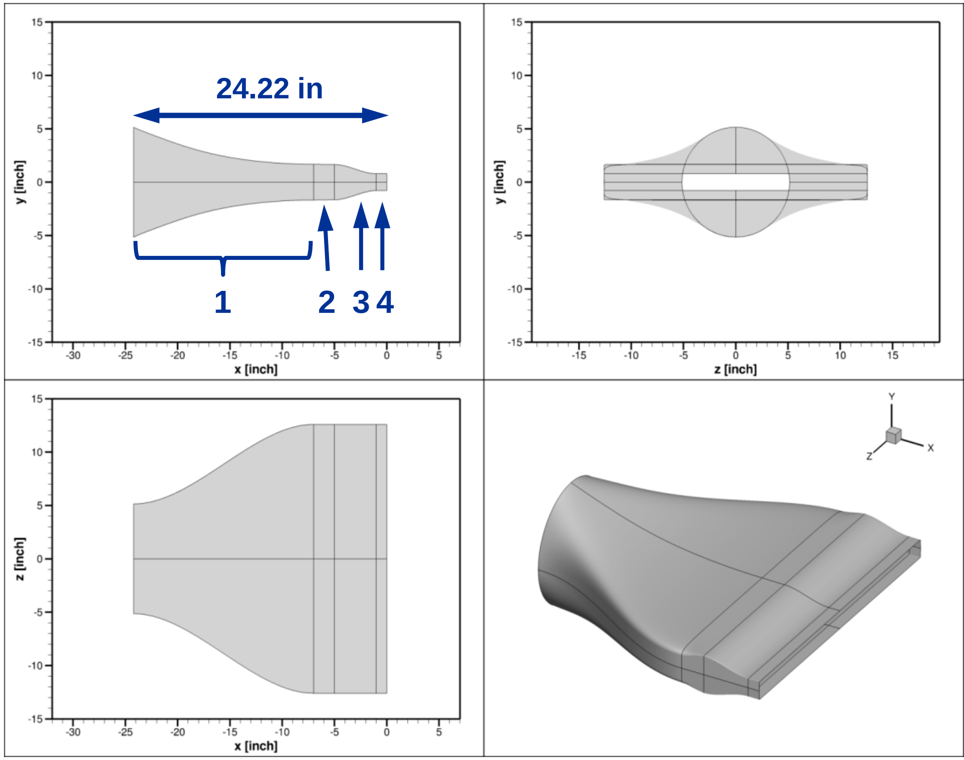


Non-smooth flow lines.

A16.6 Nozzle Design: Segmented Approach

- For greater control over HAR nozzle design, wrote code that generated nozzle in segments.
- Each segment focused on changing one or two aspects of geometry (e.g., contraction, span, cross-section shape).
- A16.6 nozzle consisted of 4 segments:
    1. Transition from circular to order 10 superellipse; grow major axis (span) to nozzle exit width via cubic polynomial; maximum divergence angle less than 33°; constant area.
    2. Transition from order 10 superellipse to order 100 via exponential function; constant area.
    3. Contract area to nozzle exit area (<u>100% of total contraction</u>) using cubic polynomial for minor axis (height).
    4. Constant area and shape to nozzle exit.

A16.6 Nozzle Design

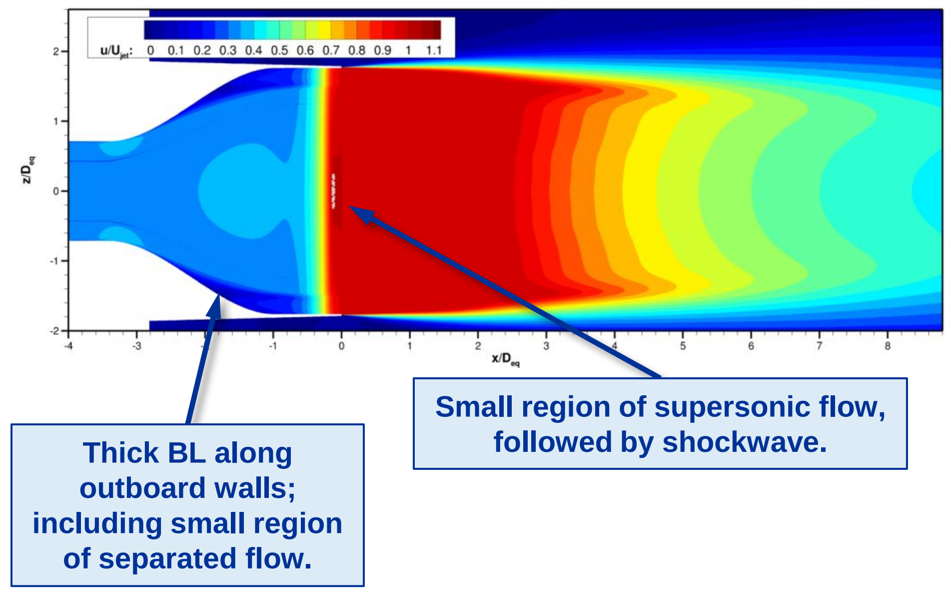


A16.6 Nozzle Screening Simulation

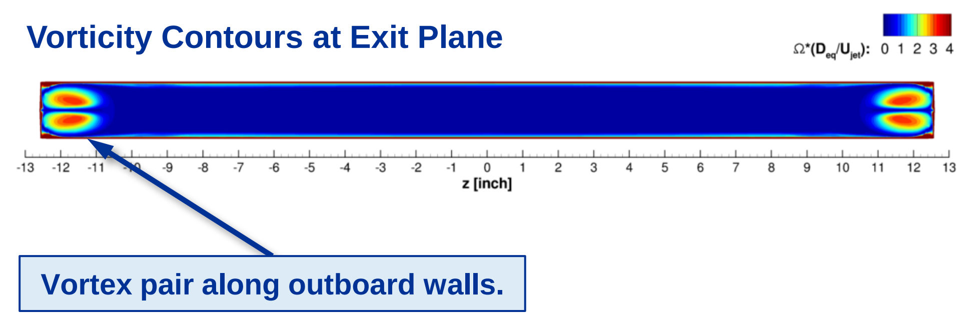
- A16.6 nozzle design still had undesirable flow features:
  - Thick BL along outboard walls (appears thicker than A16.2 design).
  - Small region of separated flow (that does reattach).
  - Small region of supersonic flow at nozzle exit.
  - Pair of counter-rotating vortices along outboard walls.

- Is it possible better distribute the flow towards the outboard walls as the span grows?

Velocity Contours Along x-z Symmetry Plane



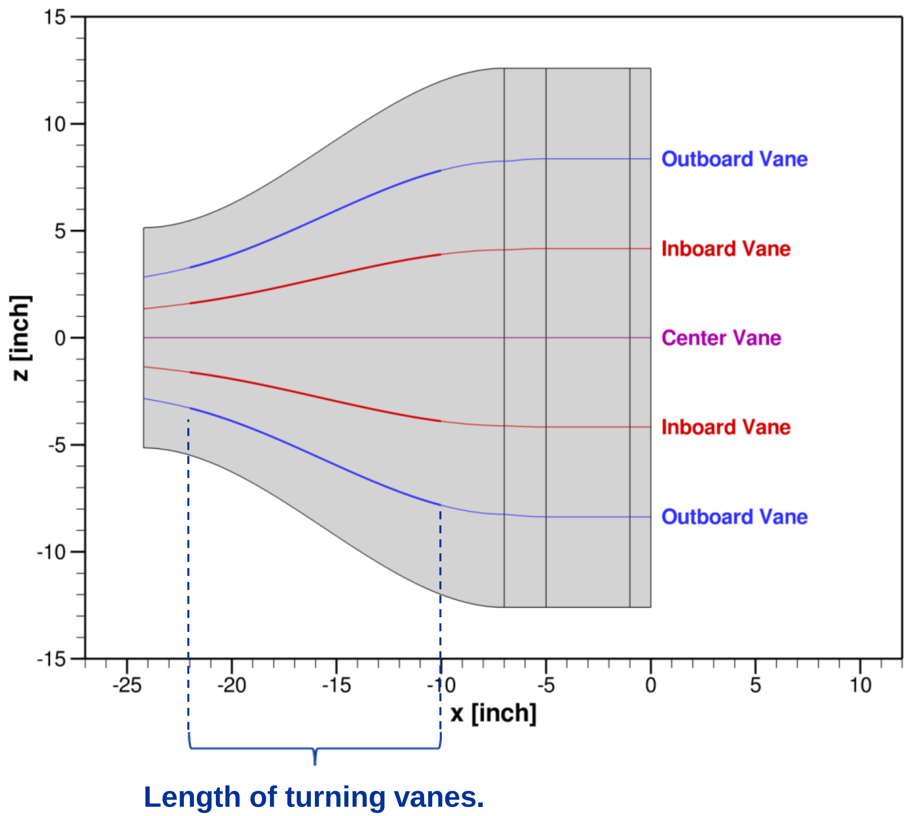
Vorticity Contours at Exit Plane



Adding Turning Vanes to the A16.6 Nozzle

- Turning vanes added to divide cross-sectional area into six equal areas.
- Grid zonal interfaces placed along locations of turning vanes.
  - Wall boundary condition used to model vane.
- Vanes modeled as infinitely thin and inviscid.
- Low-cost method for screening simulation to determine whether vanes distribute flow outwards.
- A16.6-vaneA nozzle included inboard and outboard vanes.

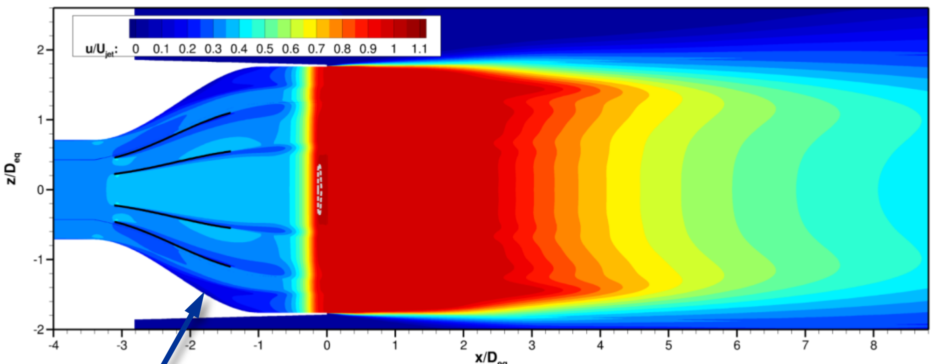
A16.6 Nozzle Design with Turning Vanes



A16.6-vaneA Nozzle Screening Simulation

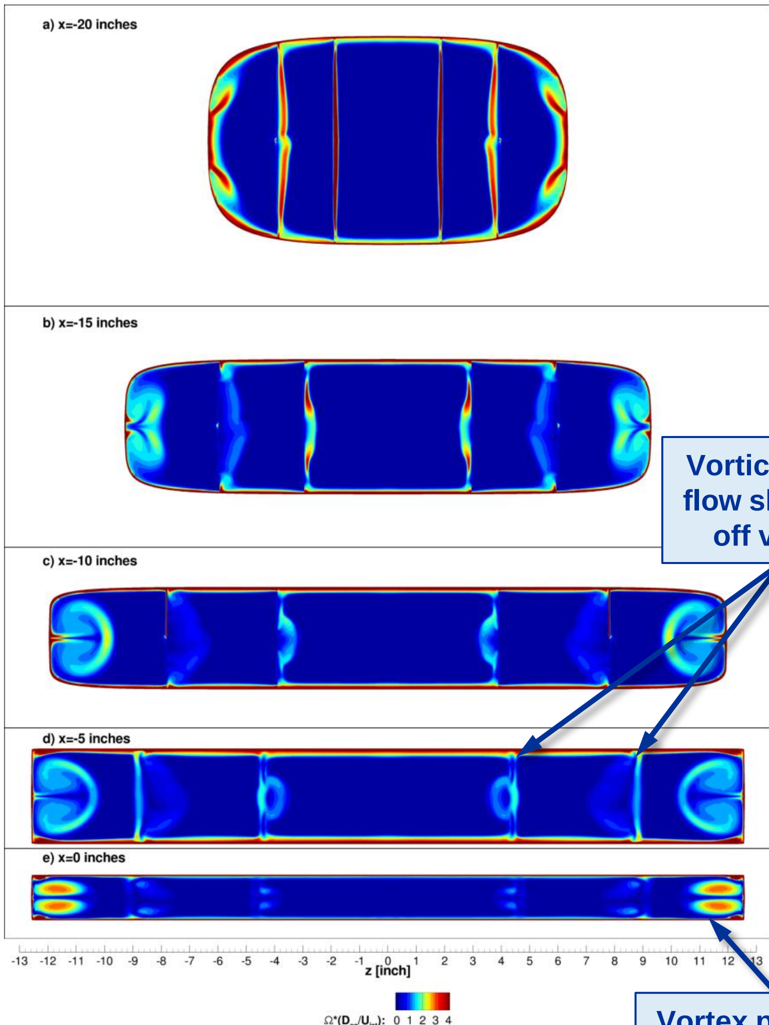
- Turning vanes were successful at distributing flow towards outboard walls and reducing BL.
  - BL remained fully attached.
- Turning vanes did produce vorticity disturbances near the nozzle exit from shedding off the vanes.
  - Non-uniformity would be amplified into actual wakes if vanes modeled with viscous boundary condition.

Velocity Contours Along x-z Symmetry Plane



Thick BL persists along outboard walls; fully attached flow.

Vorticity Contours Inside Nozzle



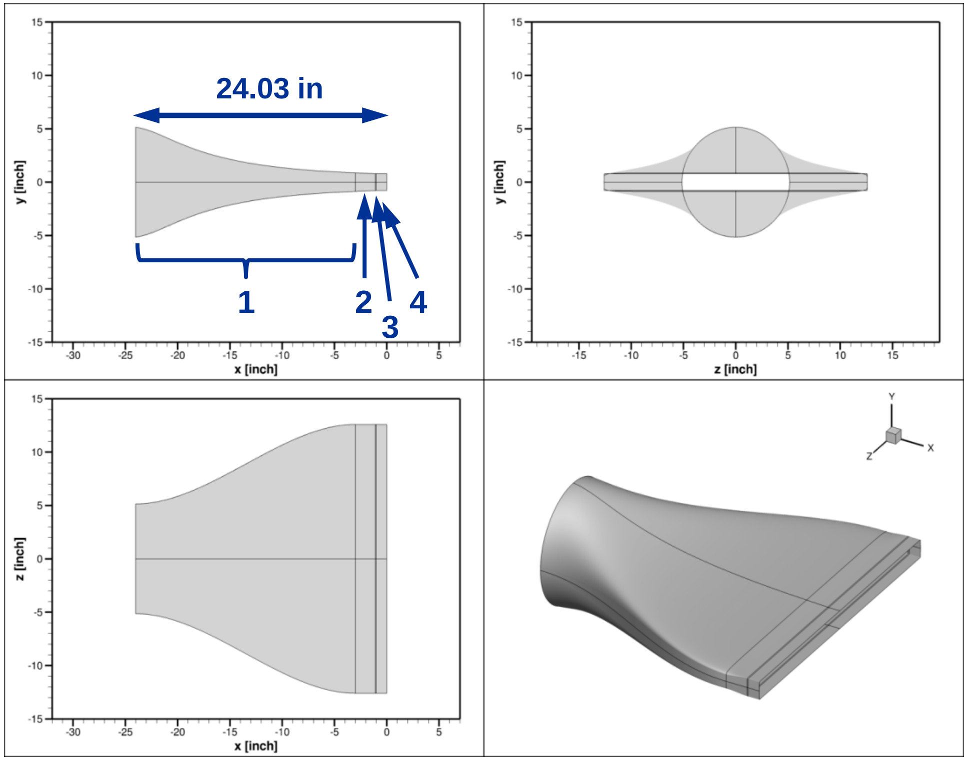
Vorticity from flow shedding off vanes.

Vortex pair along outboard walls.

A16.7 Nozzle Design

- Continued the segmented nozzle design approach
- Included area contraction through Segments 1-3.
- A16.7 nozzle consisted of 4 segments:
    1. Transition from circular to order 10 superellipse; grow major axis (span) to nozzle exit width using cubic polynomial; maximum divergence angle less than 28°; linear area contraction, 91.3% of total contraction.
    2. Transition from order 10 superellipse to order 100 via exponential function; linear area contraction, 8.3% of total contraction.
    3. Complete linear area contraction, 0.4% of total contraction.
    4. Constant area and shape to nozzle exit.

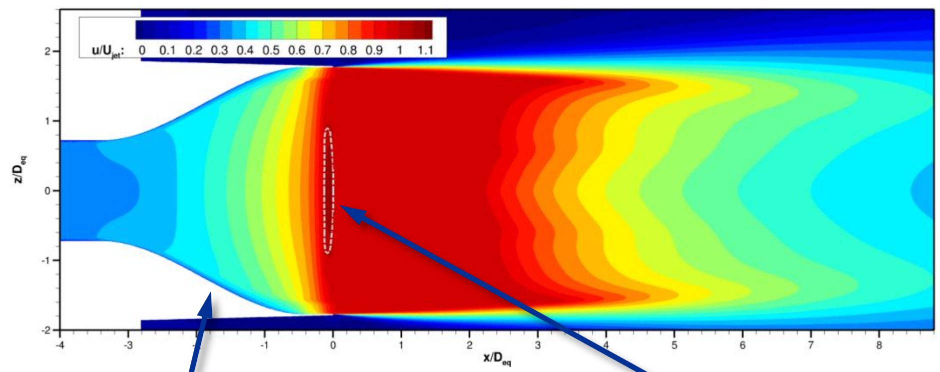
A16.7 Nozzle Design



A16.7 Nozzle Screening Simulation

- A16.7 nozzle design made some improvements, but also :
  - Thin BL along outboard walls (thinner than A16.2 and A16.6 designs).
  - Region of supersonic flow at nozzle exit, with stronger shock than previous designs.
  - Pair of counter-rotating vortices along outboard walls.

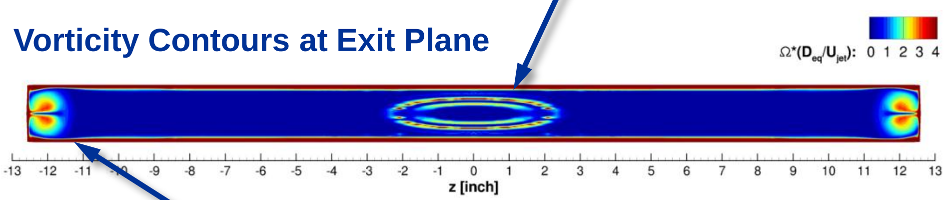
Velocity Contours Along x-z Symmetry Plane



BL along outboard wall looks thin.

Stronger shockwave at exit than observed in previous designs.

Vorticity Contours at Exit Plane

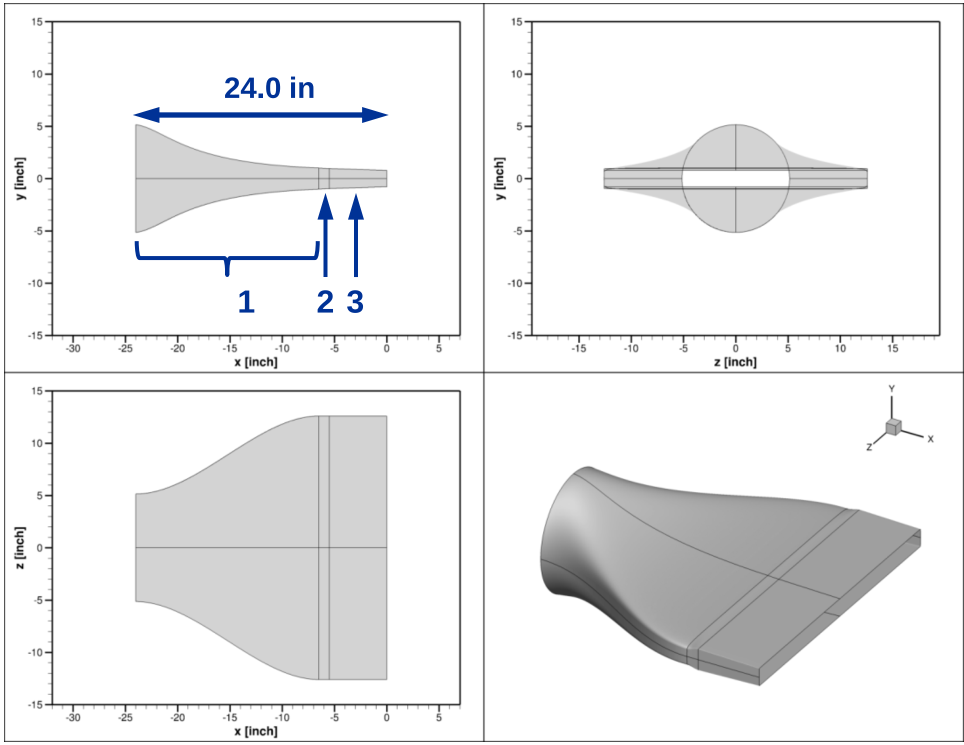


Vortex pair along outboard walls.

A16.10 Nozzle Design

- Continued the segmented nozzle design approach
- Area contraction through <u>all</u> segments.
- Lengthened segment for septa inserts to 5.5 inches; relaxed requirements so height could change if span constant.
- A16.10 nozzle consisted of 3 segments:
    1. Transition from circular to order 10 superellipse; grow major axis to nozzle exit width via cubic polynomial; maximum divergence angle less than 33°; linear area contraction, <u>75.7% of total contraction</u>.
    2. Transition from order 10 superellipse to order 100 via exponential function; linear area contraction, <u>4.3% of total contraction</u>; constant major axis (span) length.
    3. Linear area contraction, <u>20% of total contraction</u>; constant major axis (span) length and constant superellipse order; longer segment length (5.5 inches) to accommodate septa inserts.

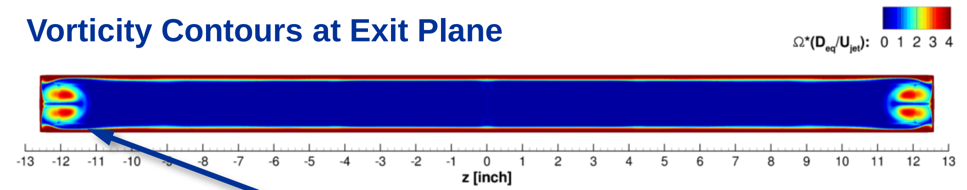
A16.10 Nozzle Design



A16.10 Nozzle Screening Simulation

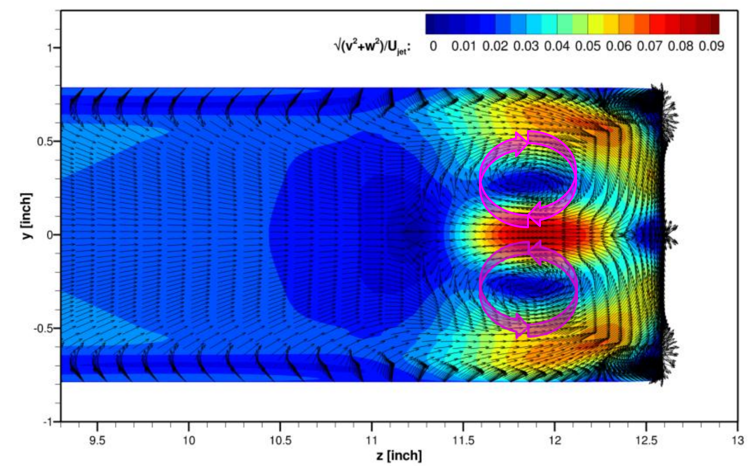
- A16.10 nozzle design looked good, with mostly uniform flow near exit:
  - BL along outboard walls not as thin as A16.7 design, but thinner than A16.2 and A16.6 designs.
  - No region of supersonic flow or shockwave at exit plane
  - Still had pair of counter-rotating vortices, about as strong as previous designs.

Vorticity Contours at Exit Plane



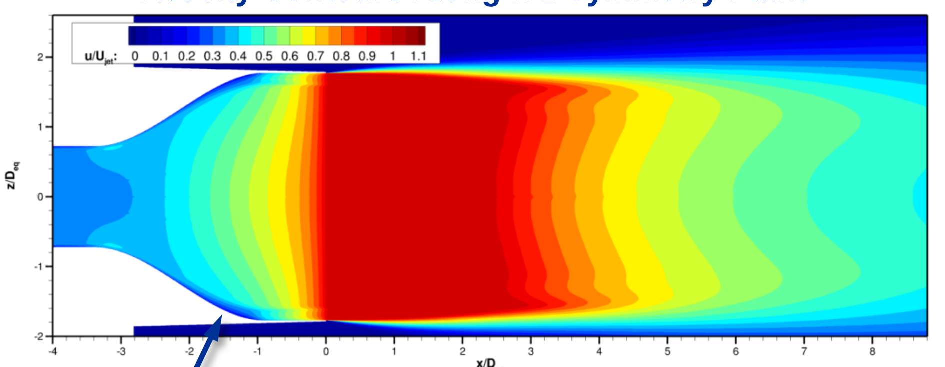
Vortex pair along outboard walls.

Cross-Stream Velocity at Exit



Counter-rotating vortex pair.

Velocity Contours Along x-z Symmetry Plane

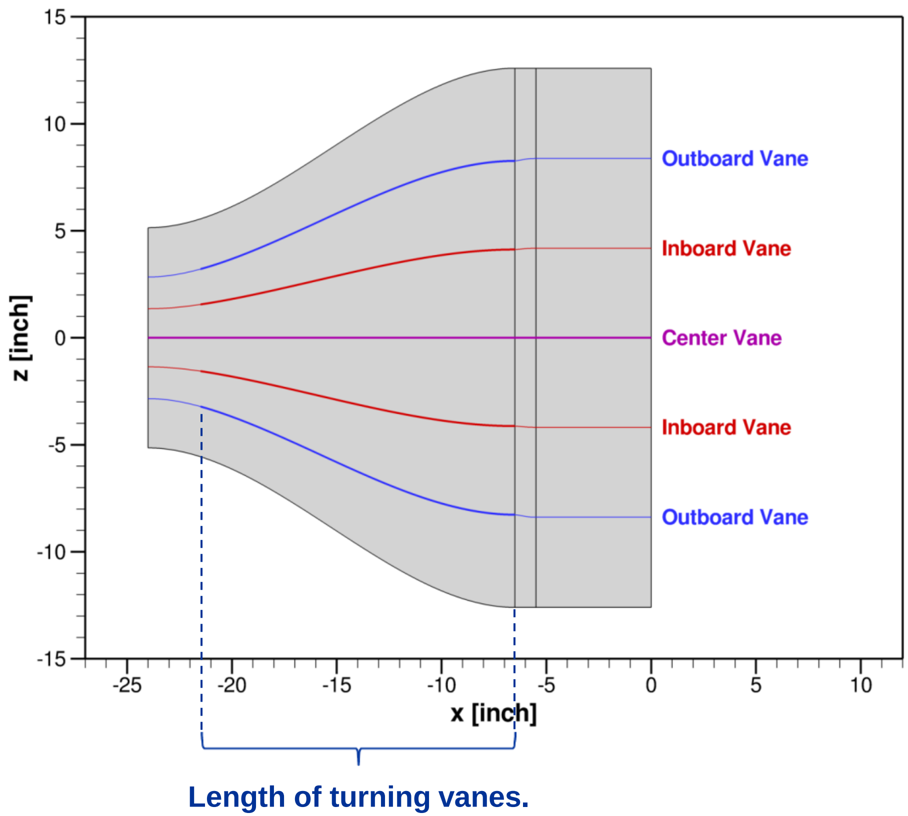


BL along outboard still appears a little thick.

A16.10 Nozzle with Vanes

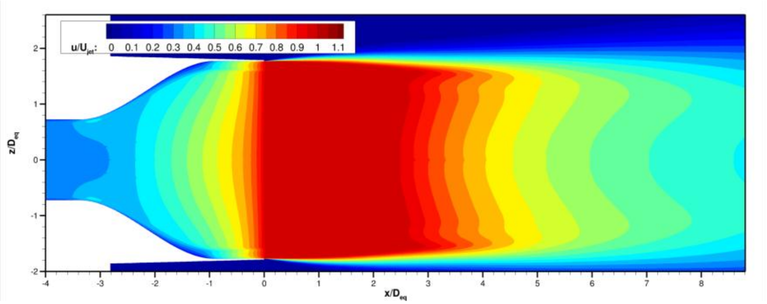
- Added turning vanes and center vane to A16.10 nozzle design
- Mechanical studies showed that center vane needed for AR=16:1 nozzle to maintain structural integrity
- Vanes modeled as infinitely thin, but now viscous

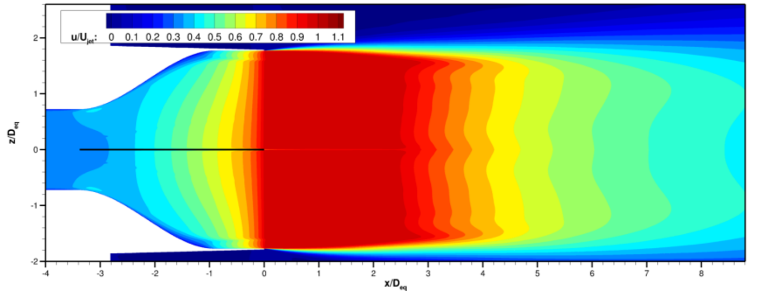
A16.10 Nozzle Design with Turning Vanes

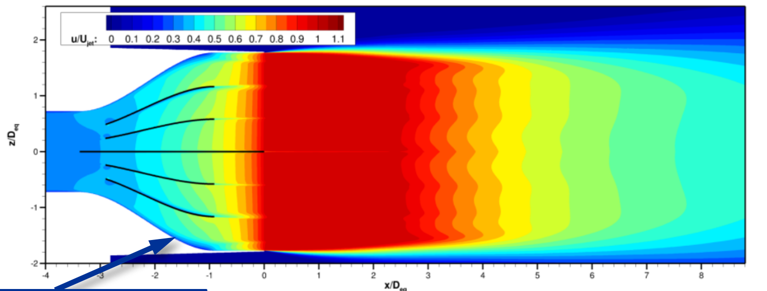


A16.10 Nozzle with Vanes

Velocity Contours Along x-z Symmetry Plane



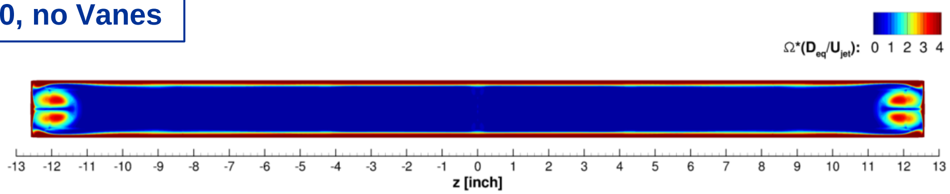




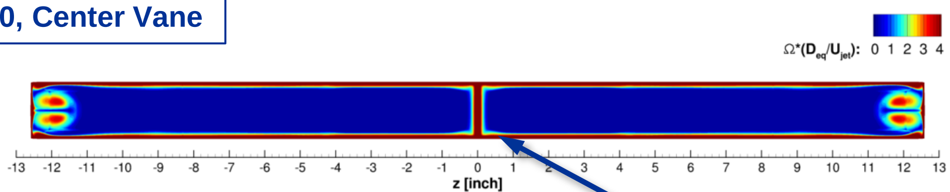
BL along outboard wall is somewhat thinner.

Vorticity Contours at Nozzle Exit Plane

A16.10, no Vanes

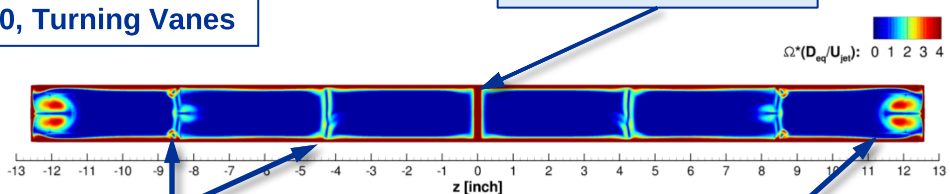


A16.10, Center Vane



Center vane creates strong wake.

A16.10, Turning Vanes



Turning vanes create significant wakes.

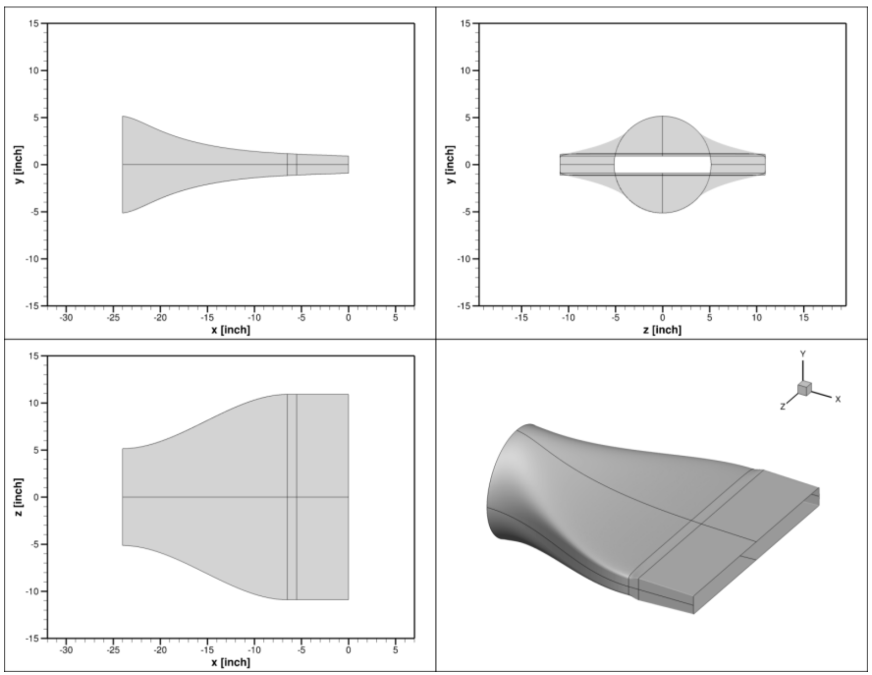
Turning vanes did not reduce vortices on outboard wall.

- Turning vanes increase non-uniformity near nozzle exit, but do not significantly redistribute flow or reduce outboard wall vortices. <u>Not worth cost.</u>

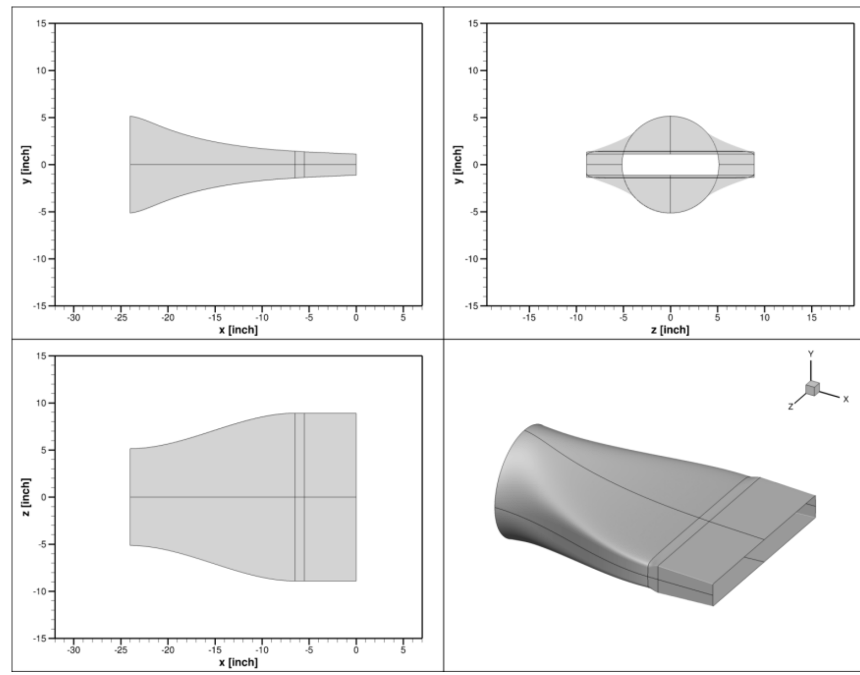
A12.10 and A8.10 Nozzle Designs

- The same code the was used to generate A16.10 nozzle was used to generate A12.10 and A8.10 nozzle (aspect ratio 12:1, 8:1).

A12.10 Nozzle Design



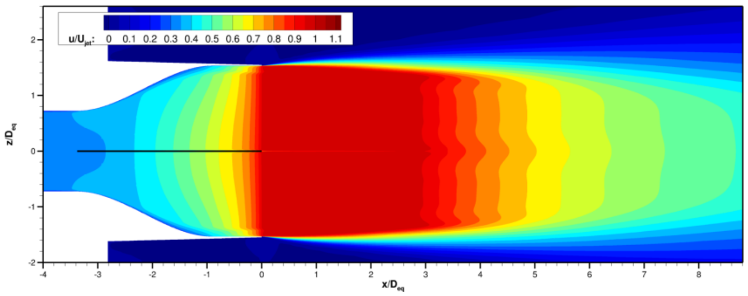
A8.10 Nozzle Design



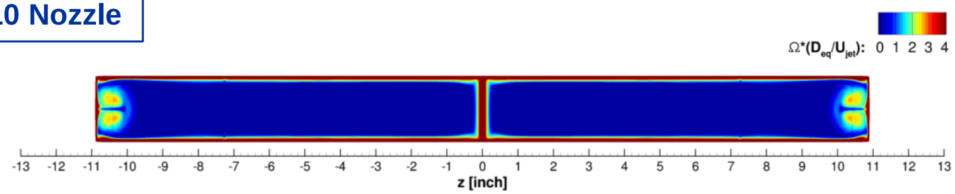
A12.10 and A8.10 Nozzle Screening Simulations

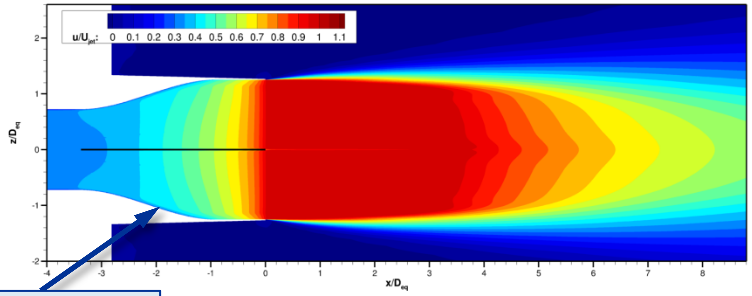
Velocity Contours Along x-z Symmetry Plane

Vorticity Contours at Nozzle Exit Plane

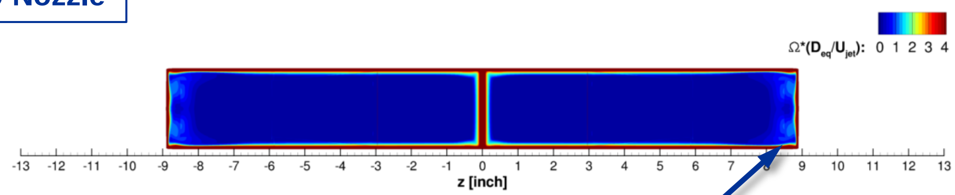


A12.10 Nozzle





A8.10 Nozzle

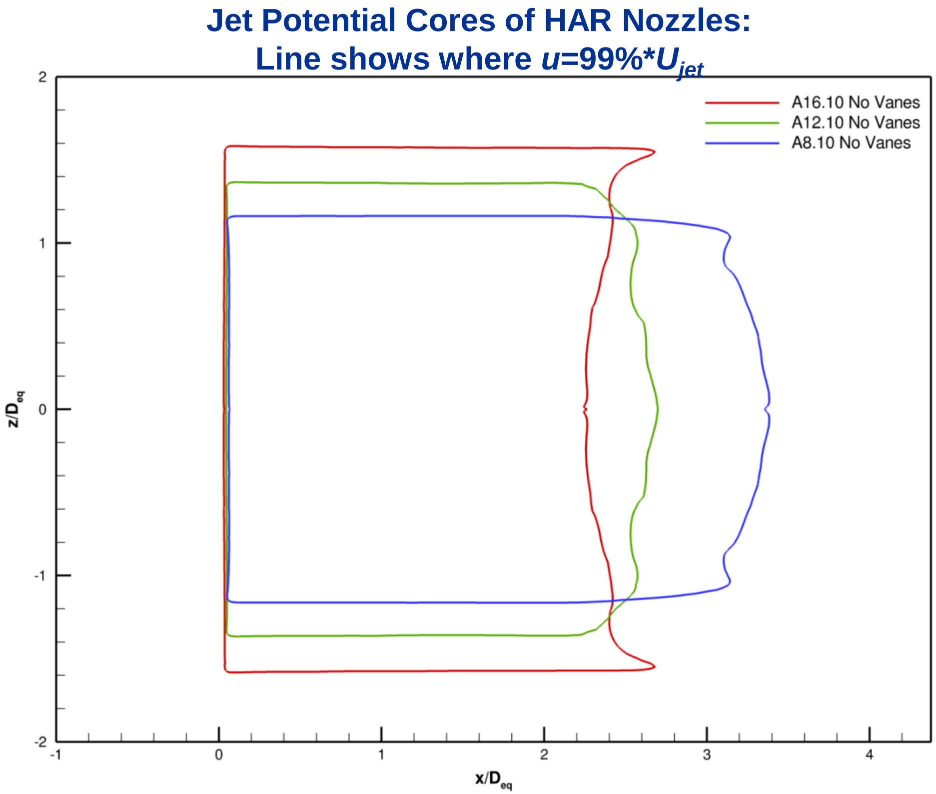


Thin BL along outboard wall.

Minimal vorticity along outboard walls.

- Smaller aspect ratio (AR=8:1) minimizes undesirable flow features:
  - BL along outboard wall remains thin.
  - Minimal vorticity and non-uniformities near nozzle exit.
- AR=12:1 also reduces undesirable flow features some, as compared to AR=16:1 nozzle.

Comparison of Nozzle Jet Potential Cores



- Jet potential core of A16.10 nozzle breaks down along centerline first, but is sustained along outboard edges longer.
- Is it possible that vortices help sustain the potential core longer along the outboard edges of the AR=16:1 nozzle?

High Aspect Ratio Nozzle Dischange and Thrust Coefficients

Nozzle	C_d	C_V
A8.10	0.9829	0.9916
A12.10	0.9809	0.9908
A16.10	0.9795	0.9886
A16.2	0.9810	0.8840

- Discharge Coefficient: $$C_d = \frac{\int_{A_{jet}} (\rho \cdot u) \cdot dA}{\rho_{jet} \cdot U_{jet} \cdot A_{jet}}$$
- Thrust Coefficient: $$C_d = \frac{\int_{A_{jet}} \left[\rho \cdot u^2 \cdot (p - p_\infty)\right] \cdot dA}{U_{jet} \cdot \int_{A_{jet}} (\rho \cdot u) \cdot dA}$$
- Clearly, discharge and thrust coefficients decrease as nozzle exit aspect ratio increases.
- Large improvement in thrust coefficient from early HAR nozzle design to final HAR nozzle design

Conclusions

- A series of three round-to-rectangular high aspect ratio convergent nozzles were designed using: AR=16:1, 12:1, 8:1.
- Custom code used to generate nozzle designs using a segment approach in order to control various aspects of geometry:
  - Transition from round to rectangular via superellipse.
  - Area contraction.
  - Nozzle span growth.
- Generating good design for AR=16:1 nozzle was most challenging, but lead to good designs of AR=12:1 and AR=8:1 nozzles.
  - Minimized potential sources of rig noise and non-uniformity in flow near nozzle exit.
  - Unable to eliminate counter-rotating vortex pair from AR=16:1 and AR=12:1 nozzle designs.
  - Greatly improved HAR nozzle thrust coefficient from early design to final design.
- Key observations:
  - Area contraction through entire length is best: maintain favorable pressure gradient and reduce chance of aerodynamic throat near exit.
  - Flow turning in short nozzles with larger AR (i.e., AR=12:1, 16:1) seems to produce counter-rotating vortex pair along outboard wall that cannot be fully eliminated.
  - Internal turning vanes reduced BL growth some, but produced wakes and did not suppress vortices.
  - As nozzle exit aspect ratio increased, discharge and thrust coefficients decreased.
- RANS simulations were valuable in screening designs of test hardware. Helped reduce risk and improve designs before nozzles fabricated.

Future Work

- Perform RANS simulations of HAR nozzles with septa and/or aft deck:
  - These configurations were tested in Jet-Surface Interaction-High Aspect Ratio (JSI-HAR) tests at NASA Nozzle Acoustic Test Rig (NATR) with limited flowfield measurements.
  - RANS simulations would provide greater understanding of aerodynamic performance not observed in experiments.

This work was supported by:
NASA Advanced Air Vehicles Program
Advanced Air Transport Technologies Project